

Repair welding process of friction stir welding groove defect

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Received 17 June 2008; accepted 27 October 2008

Abstract: The groove defect formed in the friction stir welding dramatically deteriorates weld appearances and mechanical properties of the joints owing to its larger size and penetration. Therefore, the friction stir repair welding was utilized to remove such a groove defect, and the focus was placed on the mechanical properties and microstructural characteristics of the repair joints so as to obtain an optimum repair welding process. The experimental results indicate that the groove defect can be removed by friction stir repair welding, and the offset repair welding process is superior to the symmetrical repair welding process. In the symmetrical repair welding process, a large number of fine cavity defects and an obvious aggregation of hard-brittle phase Al_2Cu occur, accordingly the mechanical properties of the repair joint are weakened, and the fracture feature of repair joint is partially brittle and partially plastic. A good-quality repair joint can be obtained by the offset repair welding process, and the repair joint is fractured near the interface between the weld nugget zone and thermal-mechanically affected zone.

Key words: friction stir welding; groove defect; repair welding process; mechanical properties

1 Introduction

As a new and promising solid state welding process developed in recent years[1–2], friction stir welding (FSW) is characterized by the high welding quality, low production cost and low welding distortion, and thus can be utilized to weld some materials that are difficult to fusion weld[3–6]. However, in the fast development and application of the FSW process, it has been known that welding defects may be formed during FSW when improper welding parameters or technological conditions are used[7–10], and such defects as groove, cavity and kissing bond have significant influence on the mechanical properties of the joints[11–13]. Therefore, the repair welding process of defect-existent joints attracts much attention, but the related research is lack. In the two published papers, one is on the repair welding technology of the defect produced during friction stir welding owing to the rupture of pin tool[14], and the other is on the friction stir processing technology of the crack formed in the aircraft wing structure[15]. Among the defects mentioned above, groove defect dramatically

deteriorates weld appearances and mechanical properties of the joints owing to its larger size than the others[11], accordingly the groove defect is chosen as a study object for repair welding in the present work, and FSW is still used as the repair welding process. The focus is placed on the mechanical properties and microstructural characteristics of the repair joints in order to obtain an optimum repair welding process and reveal the decisive factor for controlling the mechanical properties of repair joints.

2 Experimental

The base metal used in this study was a 2219 aluminum alloy plate of 7.5 mm in thickness, whose chemical compositions and mechanical properties are listed in Table 1. The plate was cut and machined into rectangular welding samples of 300 mm in length and 100 mm in width. After cleaned by acetone, the samples were longitudinally butt-welded and then repair-welded using an FSW machine (FSW-3LM-003). The welding tool pin was designated as a frustum contour and possessed right-handed threads.

Foundation item: Project supported by the Program of Excellent Team in Harbin Institute of Technology, China; Project(2006BAF04B09) supported by the National Key Technology Research and Development Program of China

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DOI: 10.1016/S1003-6326(08)60313-1

Table 1 Chemical compositions and mechanical properties of 2219 aluminum alloy

Chemical composition (mass fraction)/%									Mechanical properties		
Al	Cu	Mn	Fe	Ti	V	Zn	Si	Zr	Ultimate strength/MPa	Yield strength/MPa	Elongation/%
Bal.	6.48	0.32	0.23	0.06	0.08	0.04	0.49	0.20	432	315	11

For the convenience, we define that the joint or weld directly formed from the base metal is initial joint or initial weld, while the joint or weld formed after repair welding of the initial joint or initial weld is repair joint or repair weld. With regard to repair welding, there were two repair processes. One was symmetrical repair welding process in which the centerline of the repair weld was consistent with that of the initial weld with groove defect; the other was offset repair welding process in which the centerline of the repair weld was located in the groove position. In order to decrease the difference of microstructures and mechanical properties on the advancing side (AS) and retreating side (RS) of the repair weld, the direction of repair welding was considered to be opposite to that of the initial welding. Based on the previous experimental results, the initial joints with groove defect and the good-quality repair joints can be produced by using the technological parameters listed in Table 2.

Table 2 Welding technological parameters for initial joints with groove defect and good-quality repair joints

Joint sort	Rotation speed/(r·min ⁻¹)	Welding speed/(mm·min ⁻¹)	Pressure/kN	Tilt angle/(°)
Initial joints with groove defect	1 000	200	4.6	2.5
Good-quality repair joints	600	200	4.6	2.5

After welding, all the joints were cross-sectioned perpendicular to the welding direction for metallographic analyses and tensile tests using an electrical-discharge cutting machine (DK-7718B-CG). The cross-sections of the metallographic specimens were polished with a diamond paste, etched with Keller's reagent (150 mL water, 3 mL nitric acid, 6 mL hydrochloric acid and 6 mL hydrofluoric acid), and analyzed by optical microscope (OM, Olympus-MPG3) and scanning electron microscope (SEM, Hitachi-S4700) with an energy dispersive spectrometer (EDS).

The configuration and size of the transverse tensile specimens were prepared with reference to China National Standard (GB2625—89). The room temperature tensile test was carried out at a crosshead speed of 1 mm/min using a computer-controlled testing machine

(Instron-1186), and the tensile properties of each joint were evaluated using three tensile specimens cut from the same joint. After tensile test, the fracture features of the joints were analyzed by OM and SEM mentioned above.

3 Results and analyses

3.1 Tensile properties of joints

Fig.1 shows the tensile test results of the initial joints and corresponding repair joints. It can be seen that the initial joint with groove defect has considerably low mechanical properties, namely, the tensile strength of 152 MPa and the elongation of 1.6%. This implies that the groove defect has resulted in an enormous deterioration of the mechanical properties of the joints.

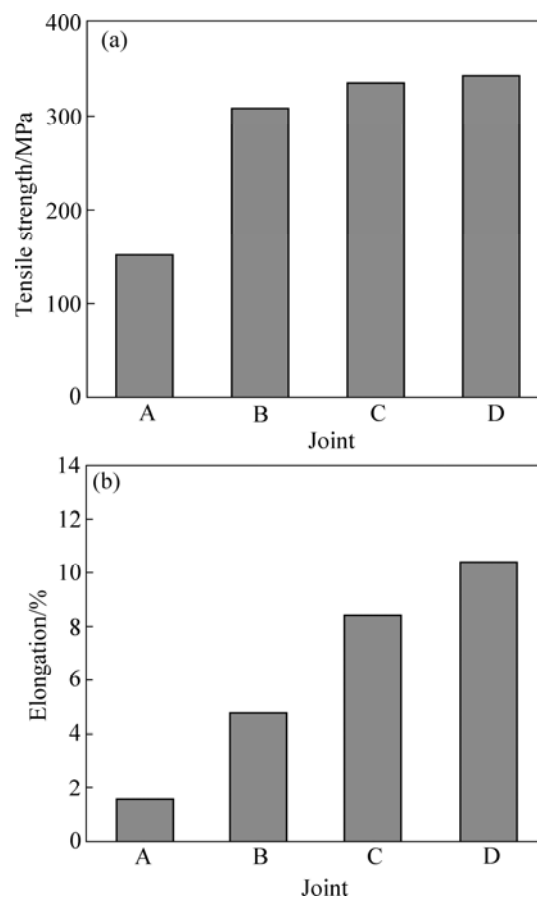


Fig.1 Mechanical properties of initial joints and repair joints (A—Initial joint with groove defect; B—Symmetrical repair joint; C—Offset repair joint; D—Good-quality initial joint): (a) Tensile strength; (b) Elongation

After the groove defect is removed by different repair welding processes, the mechanical properties of the joints are improved to different extents.

When the symmetrical repair welding process is chosen, the tensile strength and elongation of the repair joint are 308 MPa and 4.8%, respectively. However, when the offset repair welding process is utilized, the tensile strength of the repair joint is up to 335 MPa, equivalent to 78% of that of the base metal, and the elongation of the repair joint is up to 8.4%, equivalent to 77% of that of the base metal. Obviously, both repair welding processes are able to improve the mechanical properties of the joints with groove defect, but the offset repair welding process is superior to the symmetrical one and can produce good-quality repair joints that meet the engineering requirements.

3.2 Microstructural characteristics of joints

Fig.2 shows typical cross-section photographs of the initial joint with groove defect and corresponding repair joints, in which the retreating side and the advancing side are denoted by RS and AS, respectively. When unsuitable FSW parameters are used (see Table 2), the plasticized material cannot be refilled to the AS from the RS near the back surface of tool pin, therefore, a continuously distributing groove defect is formed on the AS (see Fig.2(a)), thus resulting in a degradation of mechanical properties. After repair welding, the groove defect disappears in the repair joints, therefore, the mechanical properties of the joints increase.

It can be seen from Fig.2 that the offset repair joint has a relatively large weld zone because the new weld nugget formed in the repair welding and the old one formed in the initial welding are partially overlapped (see Fig.2(b)), while the symmetrical repair joint has a smaller weld zone than the offset one (see Fig.2(c)). Moreover, there is a white curve band over the weld nugget zone of the symmetrical repair joint (see Fig.2(c)), but no white curve band can be seen in the offset repair joint (see Fig.2(b)).

Fig.3 shows a further analytical result of the white curve band. The white curve band is composed of white phases, and such white phases are almost continuously distributed in the white curve band and extend to the weld surface of the symmetrical repair joint. In the meanwhile, a large number of fine cavities, 1–5 μm in size, exist around the white curve band (see Fig.3(b)). The EDS analysis reveals that the chemical composition of the white phases is consistent with that of the precipitate phase Al_2Cu in the 2219 aluminum alloy (see Fig.3(c)). That is to say, although the original groove defect is removed by the symmetrical repair welding process, a large number of fine cavity defects are formed and an obvious aggregation of hard-brittle phase Al_2Cu

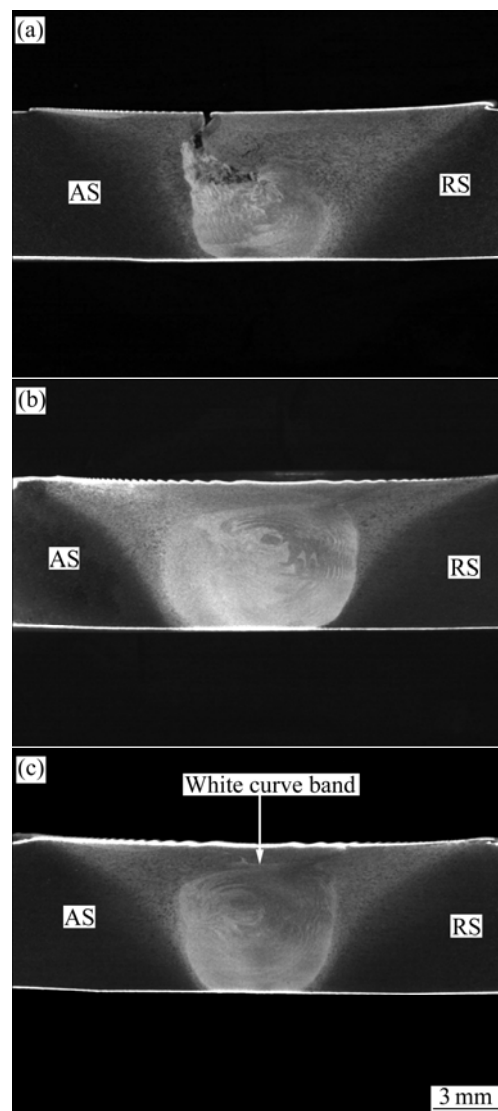


Fig.2 Cross sectional morphologies of initial joint with groove defect and its repair joints: (a) Initial joint; (b) Offset repair joint; (c) Symmetrical repair joint

occurs in the repair joint. Therefore, the white curve band is a weak location and weakens the mechanical properties of the symmetrical repair joint.

3.3 Fracture features of joints

The initial joint with groove defect is fractured at the defect location during the tensile test, and the repair joints are fractured on the RS of the welds. However, the specific fracture locations of the repair joints are different due to different repair welding processes, as shown in Fig.4. The fracture path of the offset repair joint is linearly inclined at a certain degree to the weld surface, and the fracture occurs near the interface between the weld nugget zone and thermal-mechanically affected zone (see Fig.4(a)). The symmetrical repair joint is fractured at the weld nugget zone on the RS of the weld, and the fracture path is zigzag, composed of AB,

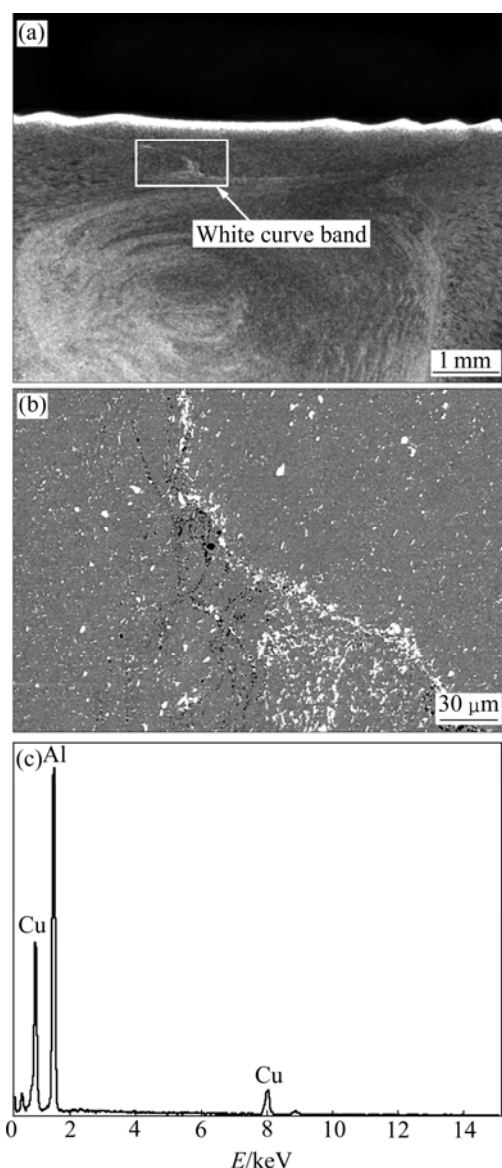


Fig.3 Morphologies of white curve band and its EDS result of symmetrical repair joint: (a) OM image of weld cross-section; (b) SEM image of white curve band; (c) EDS spectrum of white phase

BC and CD sections (see Fig.4(b)). It can be seen that AB section is consistent with the fracture path of the offset repair joint, illustrating that AB section is the intrinsic weak location in the friction stir welded joint. Because the location of CD section is corresponding to that of the white curve band shown in Fig.2(c), it can be deduced that the symmetrical repair joint is fractured along the white curve band during the tensile test, further confirming that the white curve band is the weak location of the symmetrical repair joint, as mentioned above. BC section is a transition one between AB section and CD section, and its deformation and fracture are inevitable after AB and CD sections are first deformed and fractured.

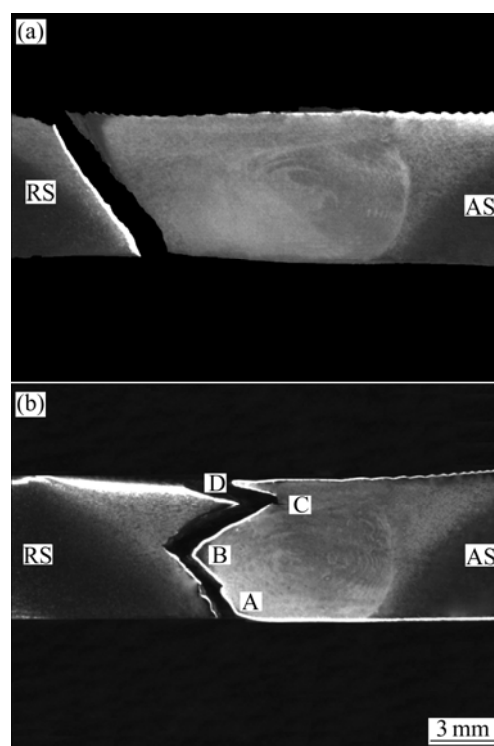


Fig.4 Fracture locations of repair joints: (a) Offset repair joint; (b) Symmetrical repair joint

In order to further reveal the fracture features of the two kinds of repair joints, the tensile fracture surfaces of the repair joints are analyzed, as shown in Fig.5. It can be seen that the offset repair joint and AB section of the symmetrical joint have almost the same plastic fracture features, i.e. larger dimples and embedded precipitates at the bottom of the dimples (see Figs.5(a) and (b)), indicating that an extensive plastic deformation has occurred. In contrast to AB section, BC section is characterized by the small and shallow dimples, implying that the plastic deformation resistance increases and the ductility decreases. With regard to CD section, there is no dimple on the fracture surface and the fracture is brittle, thus confirming that joint is fractured along the white curve band.

4 Conclusions

1) The groove defect that has a significant influence on the mechanical properties of the joints can be removed by friction stir repair welding, but different repair welding processes exhibit different repair results. The offset repair welding process is superior to the symmetrical repair welding process, and the tensile strength of the offset repair joint is equivalent to that of the good-quality initial joint and is up to 78% of that of the base metal.

2) In the symmetrical repair welding process, a

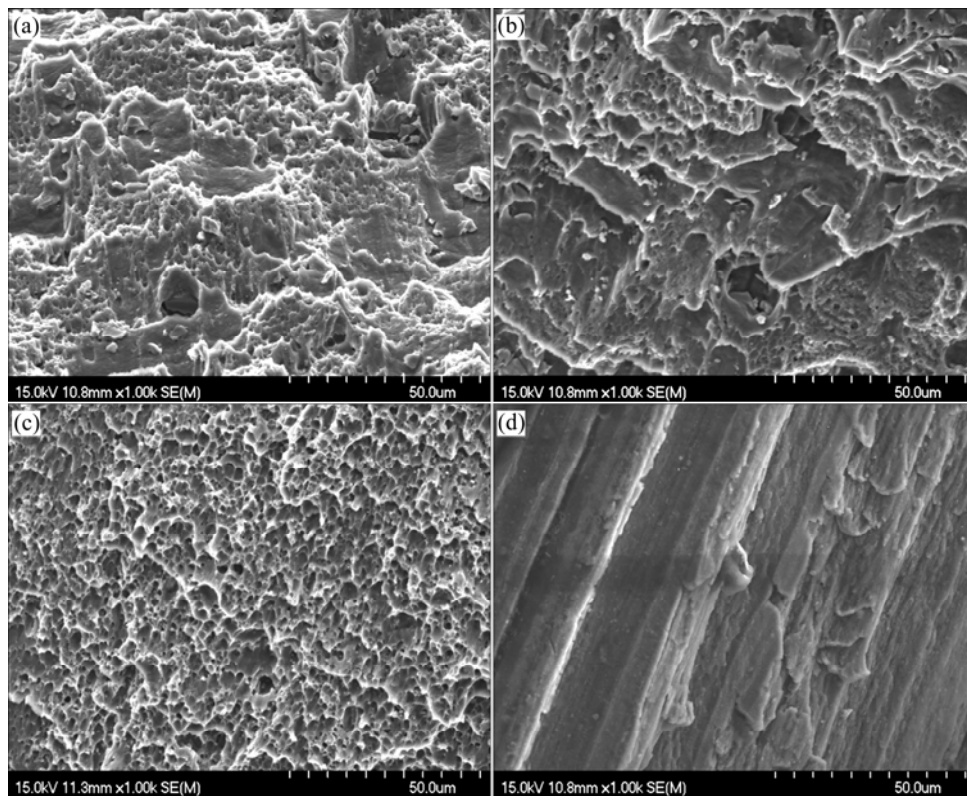


Fig.5 Morphologies of fracture surfaces of repair joints: (a) Offset repair joint; (b), (c) and (d) AB, BC and CD sections of symmetrical repair joint in Fig.4(b), respectively

large number of fine cavity defects are formed and an obvious aggregation of hard-brittle phase Al_2Cu occurs in the repair joint. Therefore, the mechanical properties of the repair joint are weakened, and the repair joint exhibits zigzag fracture path during the tensile test, and the fracture feature is partially brittle and partially plastic.

3) A good-quality repair joint can be obtained by the offset repair welding process. The repair joint is fractured near the interface between the weld nugget zone and thermal-mechanically affected zone during the tensile test, and the large dimples occur on the fracture surface or the fracture feature is plastic.

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(Edited by YANG Bing)